Research Paper | Engineering | E-ISSN No : 2454-9916 | Volume : 2 | Issue : 6 | June 2016

HORIZONTAL BATCH RETORT CONTROL THROUGH TIME DELAY COMPENSATION

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ABSTRACT

This work was focused on the possibility of time delay compensation in process control systems in thermal sterilisation of canned foods. The results represent three cases: a classical PID control system, a third-order 'exact' retort model with delay compensation, and a retort approximated by a first-order model with time delay (Smith predictor) and delay compensation. The input experimental data were collected from real objects and processes and compared to the simulated process data in the three modelling versions outlined above.

KEYWORDS: time delay in control systems, Smith predictor.

Introduction
In technological process control systems, a delay always occurs due to the physical nature of the measured, processed and regulated signals. When this delay is insignificant in relation to the dynamics of physical signals, it is ignored (considered non-existent); otherwise, it has to be taken it into account for the control purposes. The adverse effect of the delay in technological parameters on control quality is familiar from the control theory. Generally, a great delay is attributed to lack of information towards and about the process during the delay leading to significant overshooting, slow damping of the transient processes, and even to instability of the control systems.

Our previous work was focused on horizontal retorts for thermal processing of canned foods. They are multi-volume control objects characterised by great inertia and delay occurrence. These specific features determined the purpose of this work, i.e. to study the possibilities of compensating the delay in their control.

Delay Compensation in Process Control Systems
Physically, delay means slower transition of material or energy flows through the control system sections. In theory, delay is usually modelled in two ways:

- by an exponential transfer function. It called 'pure time delay'; it is used for the modelling of material and/or energy transport (transfer) devices and is most often calculated using the Padé series;
- by several consecutive standard (first-order, aperiodic) links. It is called 'transition delay', and several inseparable, inert and closed devices consecutive in the technological scheme (consecutive capacities) are modelled in this way.

The delay within a loop can occur in the control part and/or the control object. In the control part, the delay may arise in the measuring devices, the connection lines, the actuating mechanisms, the regulating elements or the digital regulating devices. It can also be caused by a greater discretisation cycle, etc.

In view of the above, it is often necessary to measure the delay in the object. This delay can occur in different stages of the whole process, i.e. in the technological parameters which are both measured and regulated, in those which are only measured and/or those which are neither measured nor regulated, but have a considerable effect on the regulation quality.

It has been proved [Hinov and Naplatanov, 1987] that a delay in the disturbance channel has no effect on the stability of the assignment channels, and that the delay should only be accounted for in regulation by disturbance or combined regulation (both by assignment and by disturbance).

It has also been proved [Hinov and Naplatanov, 1987] that the theory of feedback control systems is similar, regardless of whether the delay is in the controlling or the controlled part. Most often, it is necessary to measure the controlled part delay in relation to the controlling part (objects input-output). In the latter case, one of the ways of improving regulation is by compensating the delay in the control channel. Delay compensation is normally applied by introducing artificial feedbacks into the controlling part following the scheme in Fig. 1. According to this scheme, the compensator is like a feedback of the regulator and has a transfer function

$$W_k(s) = W_o(1 - e^{-\tau s}) \tag{1}$$

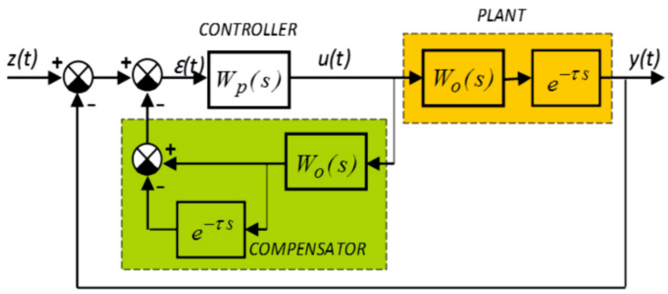

Fig.1 Scheme of delay compensation in the object

The transfer function of the regulator with the compensation is

$$W_{kp}(s) = \frac{W_p(s)}{1 + W_p(s)W_o(s)e^{-\tau s}} \tag{2}$$

The transfer function of the feedback control system is

$$\Phi(s) = \frac{W_p(s)W_o(s)}{1 + W_p(s)W_o(s)} e^{-\tau s} \tag{3}$$

It can be seen in (3) that the delay does not affect the closed structure stability since it does not participate in the denominator.

According to(1),the compensator could be regarded as two models of the object: with and without delay, the outputs of which are summed with different signs (the delay output is negative).

Practically, the delay compensation consists in passing the output signal from the object without delay to the regulator input only at the time of the delay period (lack of signal y(t)). The delayed signal of the model resets with a negative sign the signal from the model to the regulator after the period of delay has expired. It is evident that full compensation of the delay is only possible if the model reproduces the processes within the object exactly.

In [Hinov and Naplatarov, 1987], it is proved that in the proposed compensated delay schemes and the optimal controller synthesis based on a quadratic criterion of quality, the optimal control is of the PID type, and the differentiation order is proportional to the model order.

The famous Smith predictor was also based on this scheme; however it models processes by first-order models, and the regulator adjustment is elementary. For this regulator and for higher order objects, it is also necessary to have a delay greater than the attenuation time of the transition processes at the output, i.e. ($\tau > t_{nn}$) [Hinov and Naplatarov, 1987], since otherwise a parasitic component with a period equal to the delay will be inserted.

Simulation of Horizontal Retort Control by Delay Compensation

The whole heat process in the retort was divided into two consecutive parts [Madzharova* et al., 2015]:

- Heating agent power in the heating coil – water temperature in the retort ($W_a(s)$);
- Water temperature in the retort – product temperature in the package ($W_{pr}(s)$).

For these two processes, transfer functions (4) and (5) respectively were obtained in [Madzharova* et al., 2015], and their multiplication ($W_a(s).W_{pr}(s)$) was the model of the entire process within the retort. The time in (4) and (5) is in minutes.

$$W_a(s) = \frac{99}{58.27s^3 + 52.17s^2 + 12.17s + 1} \quad (4)$$

$$W_{pr}(s) = \frac{0.7121}{4.9s + 1} e^{-6s} \quad (5)$$

It was found in [Madzharova** et al., 2015] that the product temperature regulation process could be more easily and more precisely controlled by measuring and regulating the water temperature in the retort, i.e. object regulation by model (4) and forecasting the product temperature along transfer function (5).The latter helps to avoid the inconvenience of using a non-stationary thermometer to measure the product temperature.

Temperature regulation along the channel with transfer function (4) throughout the three characteristic phases: heating, constant value maintenance and cooling, is performed using an a priori familiar (base) program in time which acts as a continuously changing assignment for the regulators. The end of the sterilisation process is determined when a certain (sufficient) value of the sterilisation effect (accumulated lethality) is reached, calculated within the real sterilisation process time with a functional [Madzharova** et al., 2015]. The functional takes into account the canning product specificity, biological factors and the temperature at which the process occurs.

A PID regulator with input time delay compensation control system was accepted in this work, following the scheme in Fig.2. The SIMULINK® graphical environment was used for the scheme simulation. The program modules were masked as subsystems.

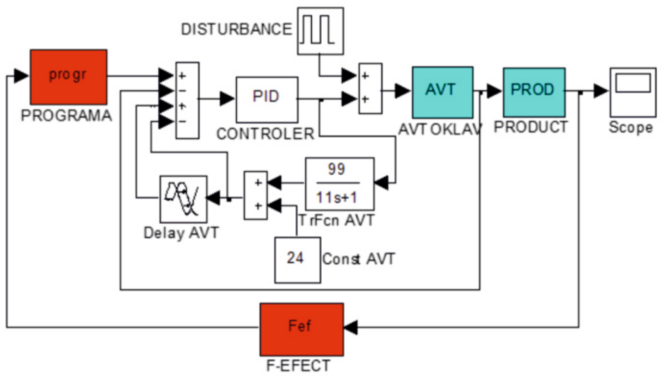

Fig.2 Control scheme with delay compensation.

In figure 2:

AVT: Process model (4);

PROD: Process model (5);

PID: PID controller;

progr: Program module for the generation and modification of the 'base' control program for a certain product;

Fef: Program module for the sterilisation effect (accumulated lethality F0) calculation;

DISTURBANCE: Disturbance generator;

TrFcn AVT: Retort (autoclave) model, without delay;

Delay AVT: Pure delay in the retort (autoclave) model;

Const AVT: Initial temperature value in the retort (autoclave).

Experimental Data and Simulation Results

A large number of simulations were made following the scheme in Fig. 2, in three versions:

- Standard regulation with a PID controller (more results have been shown in [Madzharova** et al., 2015]);
- Delay compensation when the retort was represented by a third-order 'exact' model;
- Delay compensation when the retort was approximated by a first-order model with delay (Smith predictor).

The base program used in the simulation was for the Ikra (vegetable paste) product in 0.5 glass jars (all data were kindly supplied by the Konex Tiva Ltd. company). The retort parameters and all technological requirements are also listed in [Madzharova** et al., 2015].

The results obtained after the simulation of the three versions have been shown in Fig. 3, Fig. 4, and Fig.5.

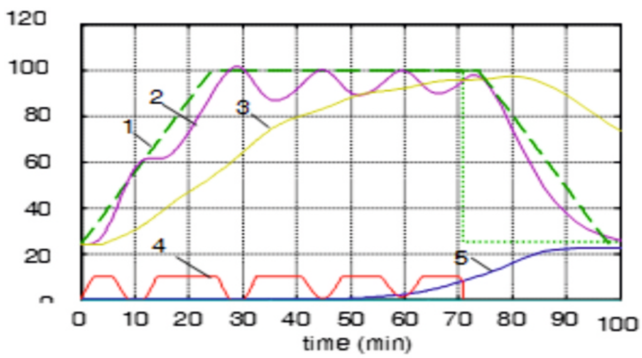

Fig.3 Control with a Classical PID

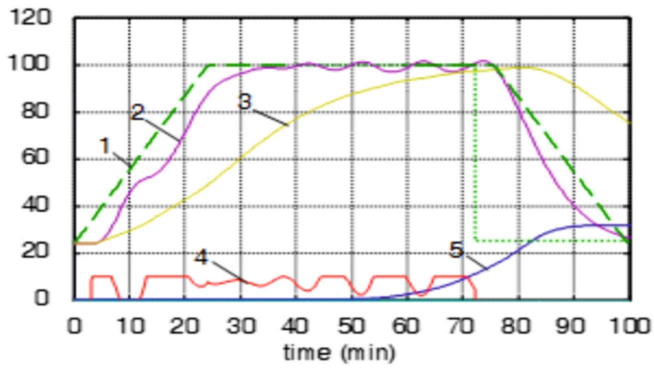

Fig.4 Compensation with an accurate model- third order

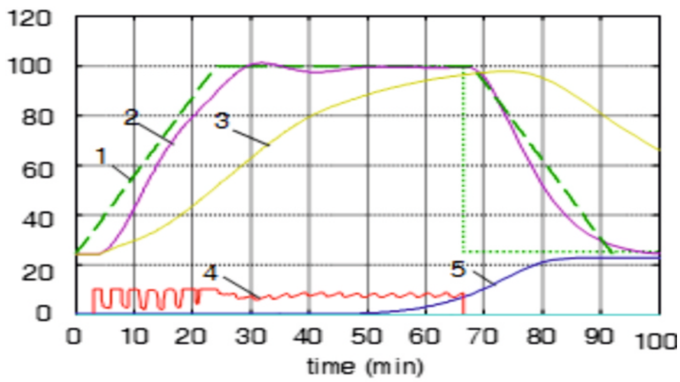

Fig.5 Compensation model - first order

In figures 3, 4, and 5:

Curve1 - program for controlling the water temperature in the retort, °C;

Curve2 - actual water temperature change in the retort, °C;

Curve3 - actual change in the product temperature in the package, °C;

Curve4 - controlling effect as % of the maximum value of the heating power (the values in the chart are x 0.1);

Curve5 - calculated sterilisation effect (accumulated lethality value F_0) in conditional minutes.

Conclusions:

The realisations shown in the figures led to the following major conclusions:

1. The operability of the retort water temperature regulating loops with delay compensation (Fig. 4 and Fig. 5) was proved.

2. The integral evaluation of proximity between the program for water temperature control in the retort (line 1) and the actual water temperature change in the retort (line 2) showed that the program was accurately realised through all process phases (heating, stabilisation and cooling).

3. Fig. 3 and Fig. 5 demonstrate that at a present sterilisation effect (accumulated lethality value) F0=20 (cond. min.), the value reached at the end of the process was ≈ 20.9 (cond. min.), but in Fig. 4 it is ≈ 32 (cond. min.).This is the static error that needs to be compensated, e.g. by changing the input parameters that control the base program.

4. The best technological results were achieved with the first order approximation model (Smith predictor – fig.5) that had a larger time constant (the whole sterilisation process lasted for around 75 min). This was due to the fact that the error between the model and the object accelerated the regulation process not only during the delay compensation but throughout the process time.

5. An accurate model of the object is needed for full delay compensation, otherwise the error calculated by the regulator would not be the actual one and the control would not be adequate.

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